Earthquakes and Structures, Vol. 3, No. 6 (2012) 783-804
DOI: http://dx.doi.org/10.12989/eas.2012.3.6.783

Options for sustainable earthquake-resistant design of concrete and steel buildings

Amador Terán Gilmore*

Universidad Autónoma Metropolitana, Departamento de Materiales,
Av. San Pablo 180, Col. Reynosa Tamaulipas, México 02200, D.F.

(Received December 3, 2010, Revised January 31, 2012, Accepted May 1, 2012)

Abstract. Because of its large contribution to the environmental instability of the planet, the building industry will soon be subjected to a worldwide scrutiny. As a consequence, all professionals involved in the building industry will need to create a professional media in which their daily work adequately solves the technical issues involved in the conception, design and construction of concrete and steel buildings, and simultaneously convey care for the environment. This paper discusses, from the point of view of a structural engineer involved in earthquake-resistant design, some of the measures that can be taken to promote the consolidation of a building industry that is capable of actively contributing to the sustainable development of the world.

Keywords: displacement-based design; damage-tolerant structure; sustainable structural engineering; structural reuse; structural recycling

1. Introduction

Amid a growing perception worldwide that immediate actions have to be taken in environmental terms, practically every field of human development has taken or promoted actions to protect the environment. Humanity faces numerous environmental challenges, such as: (1) Global warming, (2) unsustainable production and depletion of non-renewable natural resources and (3) excessive amounts of non-ecological waste and toxic materials.

One of the culprits of worldwide environmental instability is the building industry. For example, cement and steel production are two of the largest contributors to global warming and the destruction of tropical jungles. In terms of their contribution to the use and disposal of natural resources, regional building industries use from one fourth to one half of local non-renewable natural resources, and account for similar percentages of the total waste stream. At a global level, this has resulted in the depletion and degradation of important banks of materials and has contributed significantly to a storage and processing crisis of waste.

Sustainable development has been defined as one that meets the needs of current generations without compromising the ability of future generations to meet their own needs (United Nations 1987). The worldwide environmental repercussions of the building industry forces human societies to re-direct their current development. Not surprisingly, several international cement and steel

*Corresponding author, Professor, E-mail: tga@correo.azc.uam.mx

manufacturing companies have funded, during the past decades, significant research and development efforts that denote a clear compromise with sustainable development. This has not only been motivated by a growing sense of social responsibility, but by the fact that those innovations that are good for the environment usually offer competitive advantages in the field of business.

In terms of depletion of natural resources and the waste crisis, some experts have discussed the need to significantly reduce the amount of natural resources that the building industry takes every single year from nature (Gao *et al*. 2001, Thormark 2002, Oikonomou 2005, Thormark 2006). A world that demands innovation in building practices will very likely establish concrete actions that stimulate ecological practices, and discourage the abusive use of natural resources. In terms of ecological stimulus, many countries have designed green mortgages, which reward the use of green technologies for the construction and operation of dwelling units. In terms of discouraging waste, consider the taxation of waste and natural gravel, and the carbon taxes imposed by several countries to the industrial use of energy and the emission of greenhouse gasses. Within this context, it can be said that sustainable development does not confront the building industry with its commercial success, but, within a context in which civil societies will closely follow those industries that use in an intensive manner the natural resources of the planet, such development represents a matter of survival, opportunity and growth.

Important research and development programs have been undertaken to reduce the environmental impact of man-made buildings. Initially, operating a building accounted for the vast majority of its environmental impact. For instance, Thormark (2002) reports operating energies ranging from 85% to 95% of the total energy investment for buildings having 50-year service life-spans. As time passed by, practical advances in fields such as thermal insulation and solar energy substantially reduced the operating costs of buildings in such a manner that embodied (production) energy may currently involve, in low-energy dwellings, from 40% to 60% of their total energy. The important reduction achieved on the environmental cost of operating a building and thus, the increasing environmental impact of building materials, has resulted in the need for important reductions of the natural resources invested in material production and transportation.

In terms of reducing the production cost of a building, there are several possibilities that include the design and use of durable and environmental friendly structural materials, the recycling and reuse of diverse construction materials, and the use of less structural materials through the use of highly efficient structural systems. On one hand, a dynamic worldwide community of professionals is investing important research and development efforts to make possible the conception of attractive and viable options in terms of innovative low impact materials and the recycling of traditional materials (Thormark 2001, Gao *et al*. 2001, Gartner 2004, Thormark 2006, Duxson *et al*. 2007a, Duxson *et al*. 2007b). In the other hand and in stark contrast, the earthquake-resistant community has paid little attention to sustainability within a setting in which the direct and indirect environmental costs of earthquake-resistant structural systems is acquiring great importance.

In structural terms, making a structure withstand its own weight and additional vertical loads is a much easier task than making it resist simultaneous vertical and lateral loads due to gravity and earthquake, respectively. In these terms, much more care and natural resources have to be invested in the structural design and construction of earthquake-resistant structures. Current paradigms used in earthquake-resistant design and construction do not promote an efficient use of natural resources, and this problem is more deeply rooted in some developing nations. An important reason for this can be discussed by quoting Charleson (2008): "… *Now that researchers and code writers have provided structural engineers with methods to prevent structural collapse in large quakes, at least in* *developed countries attention is turning to reducing structural and non-structural damage…*". In contrast with the situation described before, many developing countries tend to use traditional structural systems to inefficiently prevent collapse, with little consideration to the socio-economic and environmental impacts of seismic damage. A good example of this is the 2010 Maule Earthquake. While there is a worldwide recognition from the community of structural engineers that the Chilean buildings successfully fulfilled the current design approach in terms of few collapses and deaths, several underlying facts, such as economical losses exceeding 30 billion dollars, and more than two million affected persons in a country with a population close to 16 million, clearly manifest the limitations of current design practice. Can the loss of natural resources on the level observed during the Maule Earthquake be considered acceptable for severe earthquakes that are likely to occur about every thirty years? Earthquake-resistant design of buildings has to change in the next years to make possible the sustainable development of earthquake prone countries. Particularly, focus has to shift from life safety-based design of traditional structural systems to damage control-based design of highly efficient innovative structural systems.

This paper discusses overall tendencies aimed at reducing the environmental cost of building production. Within this context, it is argued that it is important for structural engineers to fully identify and understand these tendencies, in such a manner that they can integrate, through a change in their design paradigms, their efforts to that of other professionals to achieve sustainable earthquake-resistant buildings. The specific examples given in the paper are not intended to describe unique solutions to a complex problem. Instead, an attempt is made to discuss how a change of framework can result in that currently available design tools and structural elements and systems can be applied in the short run to achieve lighter and safer buildings that are able to efficiently protect the natural resources invested in them. The complementation of a reduced use of natural resources with other sustainable practices, such as recycling and reuse of structural materials, creates the basis from which the paper develops the concept of sustainable earthquake-resistant design.

2. Sustainable structural engineering

Many professionals associated to or directly involved in the building industry have taken concrete actions towards making possible the conception and construction of green buildings. An example of this is the Hearst Tower, shown in Fig. 1, which is considered the first green high rise office building completed in New York City (Wikipedia 2011). The conception of the building took a number of environmental considerations. For example, the floor of its atrium is paved with heat conductive limestone, and polyethylene tubing was embedded under the floor and filled with circulating water for cooling in the summer and heating in the winter. Rain collected on the roof is stored in a tank in the basement for use in the cooling system, to irrigate plants and for the water sculpture in the main lobby. The atrium features a wide waterfall which cools and humidifies the lobby air. Overall, the building was designed to use 26% less energy than the minimum requirements for the city of New York, and earned a gold designation from the United States Green Building Council's LEED certification program.

The structural aspect was also taken explicitly into consideration during the design of the Hearst Tower. Particularly, 90% of the building's structural steel contains recycled material; and the main structural system of the building is a steel diagrid (diagonal grid), which is formed by structural steel elements that create triangular sub-structures (Moon *et al*. 2007). It is estimated that the

Fig. 1 Hearst Tower in New York

innovative structural system used 21% less steel than that associated with the construction of a standard structural system.

The fact that the structural system of the Hearst Tower was built through the use of less natural resources, and that in recent years, a number of tall buildings have been constructed using a similar paradigm, have allowed some discussion around the concept of sustainable structural engineering. In spite of the soundness of the concept and the many tools available to make it a reality, the facts are that sustainable structural engineering is still more of a concept than a reality, and that the role of the structural engineering community is instrumental in potentiating it.

3. Need for control-based earthquake-resistance design

In terms of the increasing environmental cost of structural systems and construction materials, perhaps the most important roles yet to be played by structural engineers are to significantly reduce the consumption of structural materials that go into earthquake-resistant structures, and to provide them with efficient response control in such a way as to minimize the loss of non-renewable resources through adequate damage control.

3.1 Concept

The excessive losses derived from the unsatisfactory seismic performance of some buildings designed according to worldwide accepted standard practice has created discomfort in the structural engineering community. This has gained particular importance since the unacceptably high material and socio-economic losses derived from recent worldwide seismic events (Mexico 1985, Loma Prieta 1989, Northridge 1994, Kobe 1995, Taiwan 1999, Sichuan 2008, Chile 2010). The level of loss has highlighted the need to: (1) Establish design criteria distinct from that specified in current building codes and (2) develop and implement innovative design approaches, such as performance-based design, that aim at explicitly controlling the level of damage and loss suffered by buildings built in high seismicity zones. In notable contrast with the past, the performance of modern buildings should transcend the prevention of catastrophic structural failure during severe seismic events, in such a manner that they satisfy the multiple and complex socio-economic needs of modern human societies. This implies that structural as well as nonstructural damage should be carefully and explicitly controlled well beyond the life safety and collapse prevention performance levels usually under consideration in current seismic design codes. In addition, the need for a worldwide sustainable development requires that this is achieved with unprecedented efficiency in terms of using fewer natural resources (lighter structural systems) and providing larger service lives to manmade structures.

3.2 Displacement-based earthquake-resistant design

After analyzing the reasons why several recent seismic events have resulted in excessive losses, the international community of seismic engineering has concluded that the levels of structural and nonstructural damage, as well as that in the contents of a building, is a direct consequence of excessive levels of motion (Moehle 1992, Bertero and Bertero 1992, Villaverde 1997, Takahashi and Shiohara 2004, Priestley *et al*. 2007). Innovation in earthquake-resistant design implies the design and construction of structural systems, either traditional or innovative, that can control the level of damage in the different sub-systems of a building through adequately controlling its dynamic response during seismic excitations of different intensity. Within this context, the structural properties that should be supplied to a building, independently of the structural material and structural system being used, should be such that its earthquake-resistant system is able to control its dynamic response within thresholds that are consistent with the level of damage or performance required from the different sub-systems. Limiting structural and nonstructural damage implies the control of the maximum inter-story drift index demand, which in turn implies controlling the roof displacement of a building within acceptable thresholds. Countries that lead the worldwide advancement of earthquake-resistant design have started changing their design paradigms through the formulation of displacement-based design formats and codes. A good example of this are the seismic rehabilitation guidelines included in the FEMA 356 Report (Federal Emergeny Managemente Agency 2000).

3.3 Damage-tolerant structural systems

There is a wide range of approaches and structural systems that can be used to efficiently control the dynamic response of a building (Kelly 1982, Johnson *et al*. 1998, Soong and Spencer 2002, Ventura *et al*. 2003). Far from trying to mention and discuss all options, this paper concentrates its attention on providing specific examples on how to achieve a large and positive impact in terms of sustainability by complementing available tools and technology with slight changes to current design paradigms. Attention is focused on providing the reader with specific and quantitative measures of the savings that can be achieved in terms of the reduction of structural materials that go into the super-structure of earthquake-resistant structures and, in this sense, the material discussed herein can only be considered the tip of the iceberg of the possibilities that can be offered by the international community of structural engineers.

One way of addressing the excessive levels of seismic damage in earthquake-resistant buildings is to use displacement-based methodologies, and to slightly change the current use that is given to some innovative structural systems. A promising approach to achieve safer and lighter buildings is that of damage-tolerant structural systems (Wada *et al*. 2003). In one such system, structural damage induced by earthquakes concentrates in specific structural devices, known as sacrificial elements. Their role is to act as structural fuses that protect the main or gravitational system of the building, as well as the nonstructural system, against excessive damage. Because of this, the structural rehabilitation of the structural system after severe ground motion is reduced to substituting the damaged fuses. The use of this type of system in Japan has not only resulted in lighter buildings, but promises large savings in terms of the cost and time of structural rehabilitation.

Some studies have been carried at the Universidad Autonoma Metropolitana (UAM) in Mexico City around the concept of damage-tolerant structural systems (Teran-Gilmore and Virto 2009, Teran-Gilmore and Ruiz-Garcia 2010, Teran-Gilmore and Coeto 2011). Within this context, buildings should be conceived in such a manner that vertical loads are fully supported by flexible gravitational moment-resisting frames, and earthquake-resistance is provided by a buckling-restrained bracing system. A buckling-restrained (BR) brace is a structural element that can accommodate large compressive strains without buckling. Because braces usually work in a very stable manner when subjected to tensile stresses, a BR brace is a device capable of dissipating in a stable manner large amounts of energy when subjected to severe cyclic loading. Fig. 2 schematically shows the concept of a BR brace, and illustrates its different components. Under the action of a severe earthquake, only the core of the brace yields. The core is debonded from the confining material, in such way as to minimize contact in the interface of these two materials and avoid a larger compressive strength relative to the tensile strength.

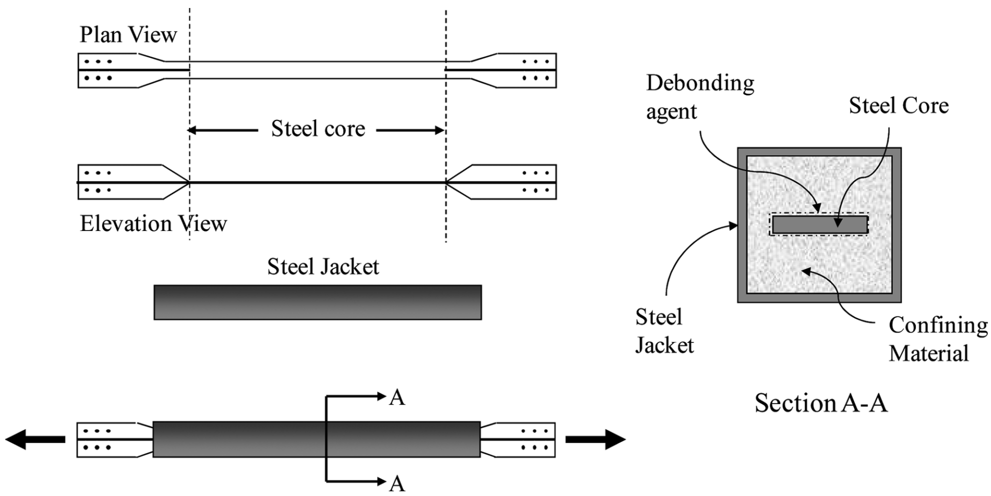

Fig. 2 Schematic configuration of buckling-restrained brace

A detailed discussion on the concept and use of BR braces can be found in Black *et al*. (2002), Uang and Nakashima (2003) and Tremblay *et al*. (2006). The experimental testing carried out in BR braces have shown a highly stable behavior when they are subjected to severe unidirectional and cyclic plastic deformation. Japan has developed several types of BR braces, and has patented several of them (Watanabe *et al*. 1988, Uang and Nakashima 2003). In fact, that country has built hundreds of buildings that have a BR bracing system as their main earthquake-resistant system. Taiwan, Canada and the United States have contributed with important experimental and practical development, and have use this type of device in the construction of new buildings and the rehabilitation of existing ones (Tremblay *et al*. 1999, Clark *et al*. 2000, Lopez *et al*. 2002, Ko *et al*. 2002, Mahin *et al*. 2004, Chen *et al*. 2004).

As discussed in detail by Teran and Coeto (2011), the UAM approach to damage-tolerant structural systems considers that under the effect of a low intensity ground motion (within FEMA requirements, such as FEMA 356, this intensity would be associated to an earthquake hazard level characterized by a probability of exceedance of 20% in 50 years) a building with standard occupation exhibits adequate performance if it satisfies the operational performance level. This implies that the gravitational and bracing systems should not exhibit significant structural damage, and that the nonstructural system should remain undamaged. Regarding performance for severe ground motion (associated to an earthquake hazard level characterized by FEMA through a probability of exceedance of 5% in 50 years), the building exhibits adequate performance if it satisfies the life safety performance level and it can be easily repaired. This implies that the gravitational system should remain practically undamaged (operational) while the bracing system develops significant plastic behavior that allows it to dissipate a large percentage of the input energy. In terms of nonstructural performance, lateral displacement should be controlled in such a manner as to protect the investment made in the nonstructural elements. Once the integrated system deforms beyond its elastic limit, structural damage practically concentrates in the braces. An undamaged gravitational system is capable of providing the braced building with significant post-yield system stiffness that stabilizes its dynamic response and reduces its residual deformations (Kiggins and Uang 2006, Teran-Gilmore and Ruiz-Garcia 2010). It is reasonable to assume that after the seismic excitation, any residual lateral deformation in the building can be eliminated by replacing the damaged braces; that is, retrofitting the building implies substituting the damaged braces.

Fig. 3 schematically illustrates the structural behavior of a damage-tolerant building. Because both the gravitational and bracing systems provide lateral stiffness to the building, it is possible to schematically model their behavior through two parallel springs. According to what is shown, the gravitational system should be flexible, in such a manner that it can deform laterally without increasing in a substantial manner its internal state of stress, and thus, its level of structural damage. Contrary to this, the bracing system provides the building with a high lateral stiffness, in such manner that it increases quickly its internal state of stress, and yields at relatively low levels of lateral displacement. Through their lateral stiffness and plastic energy dissipation capacity, the braces constitute themselves in a reliable and stable source of earthquake-resistance that controls the dynamic lateral response of the building within the displacement thresholds imposed by the required performance of the gravitational and nonstructural systems. After a severe seismic excitation, structural damage translates into residual deformation in the building due to yielding in the BR braces. Because the gravitational system should remain essentially elastic, the residual deformation should be eliminated once the yielded braces are substituted (the structural rehabilitation consists

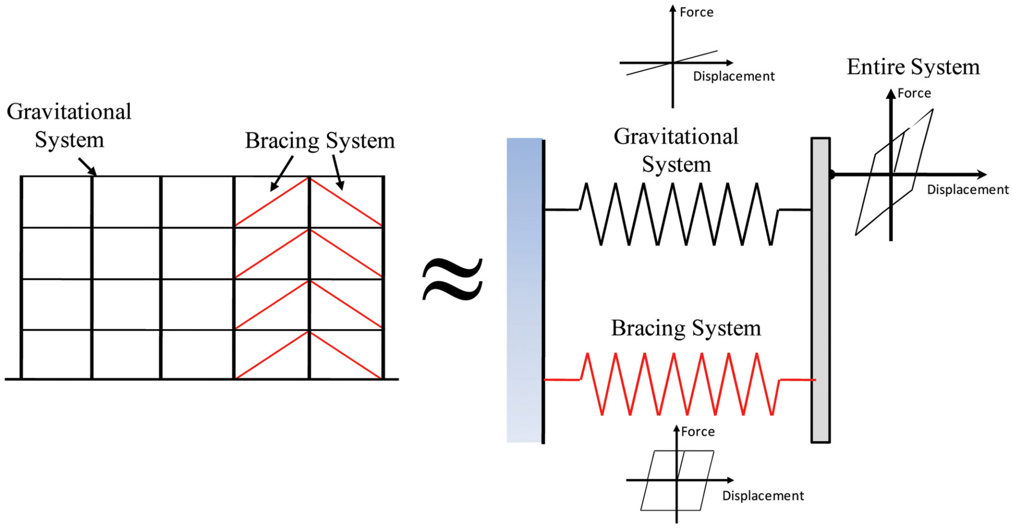

Fig. 3 Behavior of a damage-tolerant building conceived according to the UAM approache

exclusively of replacing the damaged braces). It should be noted that in terms of what is shown in Fig. 3, the structural skeleton of the earthquake-resistant building is composed by two independent and highly specialized structural systems, one to carry the gravitational loads, and the other one to provide lateral vibration control. Within this context, each system can be conceived and designed to achieve its structural role with high efficiency in terms of structural materials.

3.4 Example

Consider the seismic performance of the two four-story frames shown in Fig. 4, when subjected to a set of twenty ground motions established by the FEMA/SAC Steel Project to represent the design earthquake corresponding to firm soil sites located at the Los Angeles Urban Area and a 10% probability of exceedance in 50 years (Somerville *et al*. 1997). The frames, which are considered representative of exterior moment-resisting steel frames found in typical office buildings, were

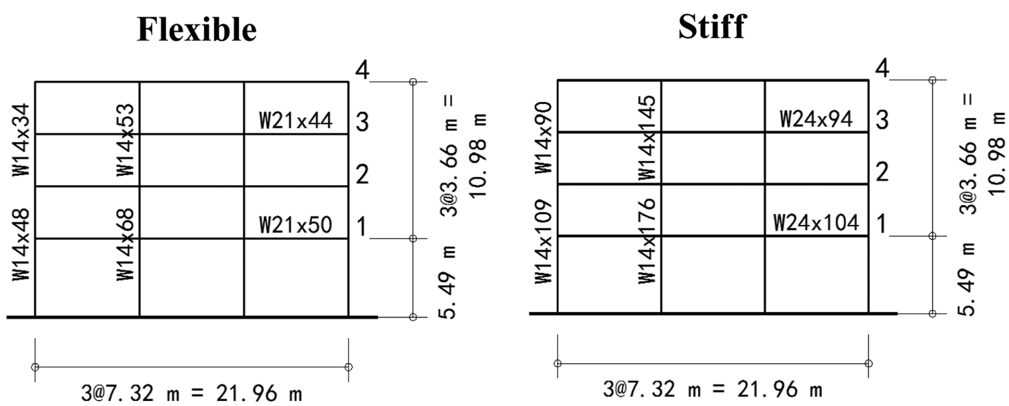

Fig. 4 Steel moment-resisting frames under consideration

Table 1 Structural properties of steel frames

Frame	T_0 (sec)	V_b/W	T_{tar} (sec)
4-story stiff	0.71	0.84	0.45
4-story flexible	1.24	0.31	0.45

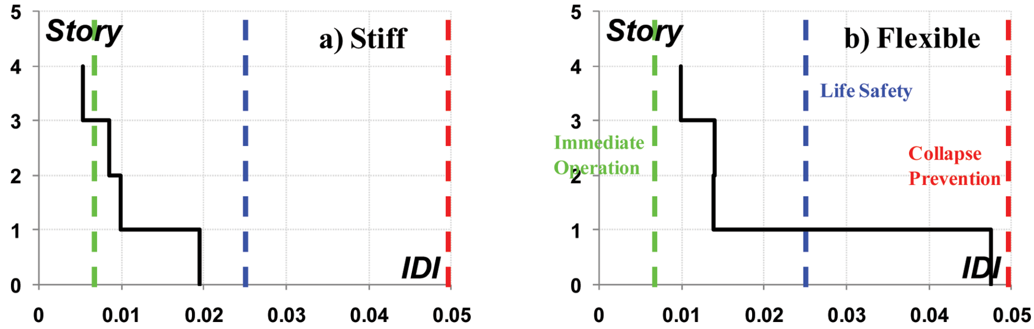

Fig. 5 Expected performance of steel frames

originally designed by Santa-Ana and Miranda (2000) according to 1994 Uniform Building Code.

Table 1 summarizes the fundamental periods of vibration (T_0) and corresponding seismic coefficients (V_b/W) estimated from nonlinear analyses of the frames (Teran-Gilmore and Ruiz-Garcia 2010). Both frames remain elastic for inter-story drift indexes that do not exceed a threshold value of 0.01. Fig. 5 summarizes the maximum inter-story drift index (IDI) demands expected in the frames according to nonlinear step-by-step dynamic analyses. The results correspond to the mean plus one standard deviation demands obtained for the twenty ground motions under consideration. In order to provide a context of the frames' performance, FEMA 356 (Federal Emergency Management Agency 2000) recommendations specify inter-story drift index thresholds of 0.7%, 2.5% and 5% for the immediate occupancy, life safety and collapse prevention performance levels, respectively.

While the stiff frame exhibits maximum inter-story drift index demands close to 2% and develops a soft story; the flexible frame exhibits much larger inter-story drifts and also develops a soft story. Note that static nonlinear analyses of the frames indicate that a 1% inter-story drift index threshold is associated to their operational performance level.

As schematically shown in Fig. 6, the frames were braced according to the displacement-based methodology developed at UAM under the consideration that their central bay was braced with two braces in a chevron configuration. While a detailed discussion of the sizing of the braces can be found in Teran-Gilmore and Ruiz-Garcia (2010); qualitatively, it can be said that the braces were sized in such a manner as to control their maximum mean plus one standard deviation maximum inter-story drift index demands within a 0.01 threshold.

While Table 1 shows the target period for which the braces were sized (T_{tar}), Fig. 7 shows that the drift demands estimated through nonlinear time-history analyses for the stories of the frames are controlled efficiently by the bracing systems within the design threshold.

It is of interest to compare the weight and seismic performance of the stiff and flexible braced frames. While in the former case, the braces provide about 70% of the total lateral stiffness of the braced frame, in the latter case this percentage is close to 90%. In terms of the weight of the

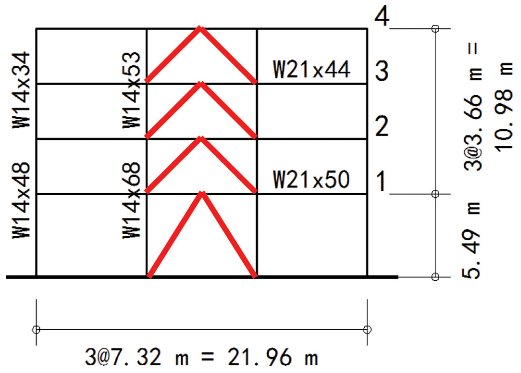

Fig. 6 Configuration of bracing system for the steel frames

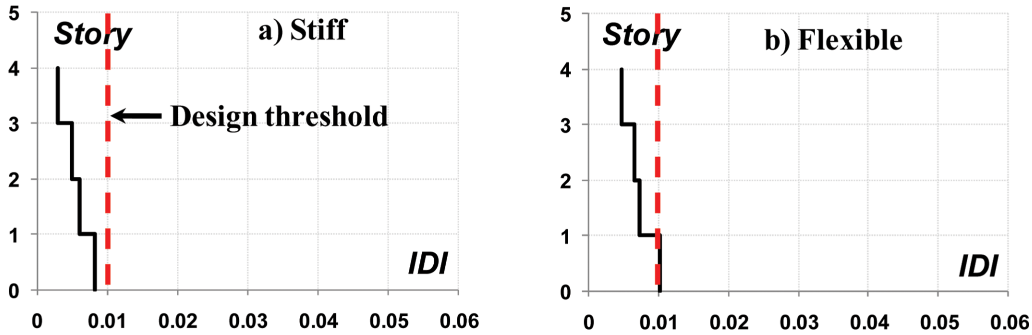

Fig. 7 Expected performance of braced steel frames

frames, the beams and columns of the stiff and flexible frames weigh 25.8 and 11.2 tons, respectively. The estimated weight for their braces and connections is 1.3 and 1.9 tons, respectively. The total weight of the structural elements of the stiff and flexible braced frames is 27.1 and 13.1 tons, respectively. In spite that the stiff and flexible braced frames exhibit a 2 to 1 ratio in terms of weight, both of them result in adequate performance. Similar results have been obtained for frames having different heights. This clearly outlines the efficiency of the use of braces within a displacement-based format to control the lateral response of buildings, and indicates that their efficiency increases significantly as the flexibility of the frames increases.

3.5 Observations

Although in the previous section simple structural systems were used to emphasize the efficiency of steel braces, it is interesting to discuss this efficiency in terms of taller buildings and full structural systems. To illustrate this, the UAM approach was used to design the twenty-four story building shown in Fig. 8 (Teran-Gilmore and Coeto 2011). On one hand, the UAM approach required the design of light moment-resisting frames with standard detailing (as opposed to ductile) to exclusively support the gravitational loads of the building. Significant savings in terms of structural materials and construction costs result from the fact that the sizes of beams and columns of the gravitational frames, as well as their standard detailing, are uniform throughout the entire

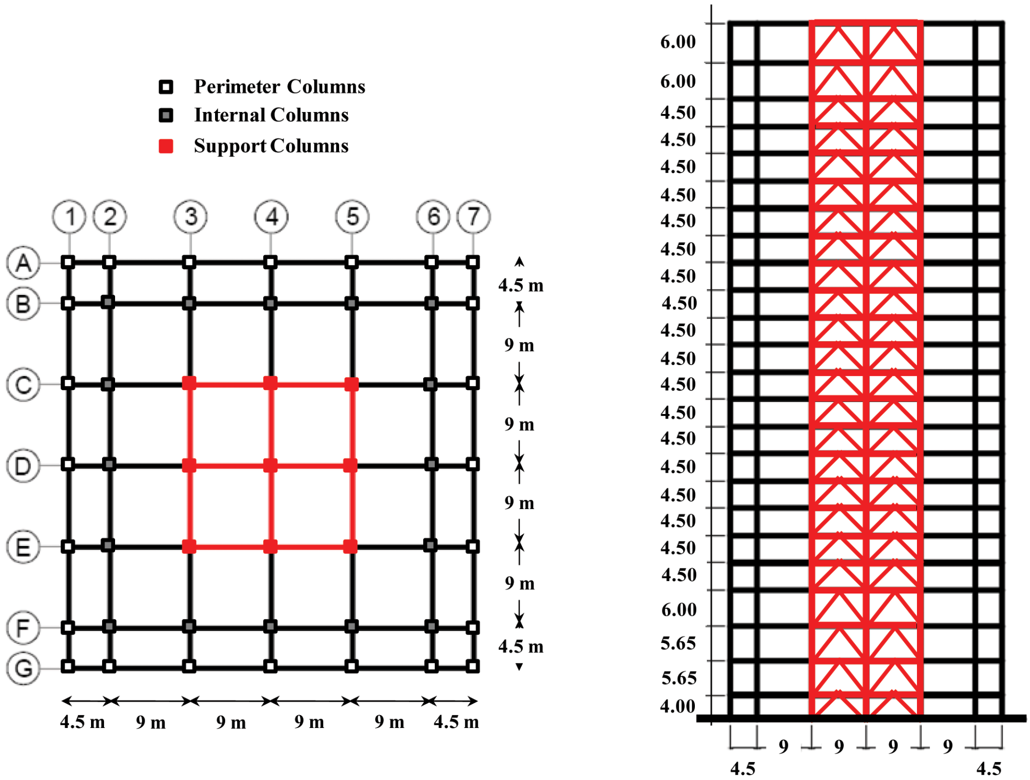

Fig. 8 Geometry and structural layout of braced twenty four-story building

building. On the other hand, the UAM approach requires the building to be stiffened through a bracing system that adds very little weight to the building.

The structural layout of the twenty-four story building is based on that used on an actual building by a prestigious structural consulting firm. That is, the displacement-based design (innovative building) represents a redesign of an actual building located in Mexico City, designed according to the local building code, and structured with ductile steel braces and composite moment-resisting frames (traditional building). Regarding the structural system without consideration of the floor system, the structural skeleton of the traditional building weighs close to 12,500 tons (3,900 tons for beams, 8,100 tons for columns and 500 tons for ductile braces). In the case of the innovative system, the structural skeleton weighs 4,800 tons (1,200 tons for beams, 3,000 tons for columns and 600 tons for BR braces). Through a format that is based on the use of demand and capacity factors, Montiel and Teran-Gilmore (2011) evaluated and compared the confidence levels for the two versions of the twenty-four story building. They concluded that the innovative version of the building exhibits larger confidence levels for seismic excitations of different intensity; this in spite of the fact that the innovative structural skeleton weighs less than half the weight of its traditional counterpart. In terms of sustainability, the above implies that through a shift in current structural paradigms, it is possible to conceive and build safer buildings through the use of fewer natural resources.

The conclusions derived from the seismic performance of the four-story frames and the twenty-four story building have been corroborated in buildings having different heights and structural configurations. Within this context, it is important to note that these conclusions are not new or unexpected. While the concept of damage-tolerant structures has been available for years, that of BR braces was proposed and experimentally tested several decades ago. Several other design approaches and structural systems can be used to achieve reliable and efficient earthquake-resistant design in terms of sustainability. Particularly and because of this, it is very difficult to answer the following question: Why sustainable earthquake-resistant structural systems have not been made a reality at a large scale?

Although so far the need for damage control in the structural and nonstructural systems has been discussed, high floor accelerations can be reflected in high levels of damage in contents such as ceilings and lights, building equipment, elevators and other contents (Villaverde 1997, Marsantyo *et al*. 2000, Comerio and Holmes 2004, Konstantinidis and Makris 2006, Kaneko *et al*. 2008). Although within a context in which the contents of a building represent a large percentage of its cultural, social and economical value, sustainable earthquake-resistant design can't be fully achieved with displacement-based formats; standard occupation buildings concentrate from 85 to 90% of their economical value and embodied energy in their structural and nonstructural systems. Just as a reference, consider that recent studies suggest that the $111 billion dollars required to repair or replace damaged components in the city of San Francisco after a high intensity earthquake, would be distributed as follows (Kneer and Maclise 2008): (1) 67% for nonstructural components, (2) 18% for structural components and (3) 15% for contents. Although damage control in the contents of a building is desirable and possible, the information required to establish practical acceleration-based formats to protect them is still not there. Under the consideration that damage to contents represents a small percentage of the total economical and environmental value of standard-occupation buildings, sustainable development of earthquake prone countries requires displacement-based control formats in the short run.

4. Structural materials

In terms of further reducing the environmental cost of a building, there are several possibilities that include the design and use of durable and environmental friendly materials, and the recycling and reuse of diverse construction materials. Although within this context structural engineers can not be considered responsible for developing knowledge, they are indeed a fundamental part of implementing it. In terms of innovation it can be said that all that is involved in the manufacturing and use of building materials is subjected to reinvention. In spite of this, in the short run concrete and steel will still be used to construct the majority of buildings in the world. In these terms, it is important to revisit the use of these materials having sustainability in mind.

4.1 Cement and concrete

After water, concrete is the most used material on Earth. It is estimated that each year close to a cubic meter of concrete is manufactured for each one of the almost seven billion persons that inhabit our planet. Cement is the source of greenhouse gases that has the largest growing rate, and because of this, it has become the third largest source of carbon dioxide with an estimated contribution of 5% of the world total (Gartner 2004).

The manufacturing process of cement results in unacceptably high levels of emission of greenhouse gases. During manufacturing, these emissions come from two main sources: (1) The heat energy required to calcinate the raw material and (2) the liberation of carbon dioxide as a result of the chemical reactions that take place during the calcination. Within the context of sustainability, it is possible to think of cements that require lower cooking energy, and that liberate less amounts of greenhouse gases. Recycling of building materials and the design of highly durable concrete mixtures should also be considered. Although this may seem excessive in terms of formulation, the fact is that large cement manufacturing companies are studying several possibilities for the development of high performance concretes that show a clear compromise towards the notion of sustainability. It is worth mentioning the Cement Sustainability Initiative, whose objectives are to increment the contribution of the cement industry to the sustainable development of the planet, and to raise the public awareness of this contribution. Research has given place to cements with a wide range of physical and chemical properties that could be classified as ecological or green, and that have emerged as novel engineering materials with the potential to form a fundamental element of an environmentally friendly construction industry (Gartner 2004, Duxson *et al*. 2007a, Duxson *et al*. 2007b).

In terms of durability, it is important to take into account that several international ecological forums have reached the conclusion that standard buildings need to be designed and constructed to exhibit larger service lives than those currently contemplated for them (roughly 50 years; see Alexander *et al*. (2008) for indicative design working lives of different types of structures). Within this context, some experts see in durability the factor that will override all other technological drivers in determining success. The possibility for periodic refurbishing of installations and contents should be taken into consideration, and this has led to concepts such as reuse of buildings. Design for durability, which targets the design of structures that do not require monitoring and/or periodic maintenance, needs to be considered by structural engineers as a fundamental part of structural design.

A promising approach to lengthen the service life of reinforced concrete is the addition of discontinuous fibers of different materials and geometric configurations into concrete mixtures. Systematic engineering of fiber concretes has proceeded at a rapid pace, in such a way that such materials have been used during the construction of full scale structures (Keoleian *et al*. 2005, Li 2007). Through improving the distribution of cracks throughout the length of structural reinforced concrete elements, the fibers tend to decrease crack widths, and allow for substantial reductions in deflections. In these terms, it can be said that the adequate balance of the properties of the fibers and those of the concrete matrix makes possible the construction of slimmer structural elements that exhibit a larger service life. The use of fiber concretes is increasing significantly in Europe because of the efforts invested in this continent to develop design recommendations and codes (Di Prisco *et al*. 2009, Walraven 2009).

Recycling building materials results in significant reductions in terms of embodied energy and demand of structural and other building materials (Gao 2001, Thormark 2002, 2006). Several researchers see the concrete industry as a potential consumer of waste materials. Consider that in the United States more than 250 million rubber tires are discarded every year, and that some studies suggest that the addition of tire particles in concrete can increase its service life through diminishing the amount and size of its cracks. The correct use of additives and special cements complemented by an adequate pre-treatment of the rubber particles have resulted in rubbcretes that have the potential to be used for structural purposes, and that exhibit substantial increase in their plastic deformation capacity and a notable resistance against corrosive environments and extreme weather conditions (Siddique and Naik 2004, Turki *et al*. 2009).

In terms of short-term actions, it is realistic to think about the possibility of recycling existing concrete for the fabrication of new concrete. Existing concrete can be triturated in such a manner that it complies with certain graduation requirements, and used as coarse aggregate in fresh concrete. This prevents the loss of valuable material, and helps reduce the problem of storage and disposal of excess waste material. The use of recycled aggregates has become a priority for the building industry of several European and Asian countries and has shown potential in developing ones (Gao *et al*. 2001, Oikonomou 2005, Corinaldesi and Moriconi 2006, Martinez-Soto and Mendoza-Escobedo 2006).

Europe has created a series of regulations that allow the classification of recycled aggregates in terms of their physical, mechanical and chemical properties (Oikonomou 2005, Etxeberria *et al*. 2007). Several studies suggest that the substitution of up to 25% of the natural coarse aggregate by recycled coarse aggregate has a minimum impact on the physical and mechanical properties of concrete (Levy and Helene 2004, Gomes and Brito 2009). Experimental tests strongly suggest that if this percentage of substitution is not exceeded, it may be possible to characterize the strength and behavior of structural elements fabricated with recycled materials, with design requirements established for normal reinforced concrete elements (Corinaldesi and Moriconi 2006, Etxeberria *et al*. 2007). Through the careful consideration of the percentage and chemical composition of recycled aggregates, several researchers have obtained adequate recycled concretes in terms of durability (Levy and Helene 2004, Gomes and Brito 2009). Currently, Europe is working on creating standards to allow for an extensive use of recycled concrete as a structural material.

4.2 Steel

Although steel is the most recycled material used in modern building construction, its global production has increased during the last five decades, in such a manner that in 2006 the annual production of steel reached 1.25 billion tons. According to recent figures, the steel industry contributes with 3 to 4% of the global production of greenhouse gases.

The technological improvements developed during the last 25 years have allowed for a substantial reduction in carbon dioxide emissions during the manufacturing of steel. In spite of the efforts invested by the worldwide steel industry to further improve the efficiency involved in the manufacturing and recycling of steel, it is expected that the next generation of significant technological advancement will not come before the 2020s (World Steel Association 2007). As for today, it is possible to identity three important manners to reduce the environmental impact of steel production: (1) The transference of technology from developed countries to underdeveloped countries to modernize their steel infrastructure; (2) a more efficient use of this material and (3) the recycling of steel and reuse of steel structural elements. Within this context, the contribution of the structural engineer to sustainable development requires, among other things, the use of innovative earthquake-resistant design methodologies that make possible the construction of safer buildings with a significant reduction on the consumption of structural steel.

4.3 Observations

Understanding the worldwide tendencies in terms of developing sustainable materials and recycling existing ones allows the structural engineer to significantly contribute to the reduction of the environmental impact of earthquake-resistant structural systems, and of the buildings they protect. Within the context of damage-tolerant structures, damage should concentrate in structural fuses. As illustrated schematically in Fig. 3, the structural elements of the main or gravitational system should survive severe earthquakes without damage. Under these circumstances, the structural engineer is in a position to stress to professionals in charge of developing new structural materials that focus should be made on durability and low environmental impact. An adequate interaction of structural and material engineers should make possible the elevation of sustainability as a design target through the integration of green material design and processing, structural durability and efficiency, and adequate earthquake-resistance.

Recycling structural materials can result in significant reduction in the embodied energy of a building and of the use of non-renewable building materials. In spite of this, it is important to understand that while recycling some materials, such as concrete, may result in larger embodied energy; recycling others, such as steel, can result in significant savings (Gao 2001). Several countries now require large percentages of building materials to be recycled, in such a manner that structural engineers in the field of earthquake-resistant design need to develop applications for recycled structural materials. Again, the concept of damage-tolerant structure and the fact that the structural elements of the gravitational system should remain undamaged during severe ground motion becomes a solid basis for the formulation of structural systems that can easily incorporate recycled building materials into their gravitational systems.

5. Reusable gravitational systems

An important tendency in terms of sustainable development is the reuse of structural materials and elements. Several studies indicate that reusing structural elements can result in significant savings in terms of embodied energy and building materials, in such a manner that reducing the impact of the built environment requires the conception, design and construction of buildings with large recycle/reuse potential (Gao *et al*. 2001, Thormark 2002). This has led some researchers to move away from the idea of demolishing buildings, and to discuss the need for buildings, and thus structural systems, that can be easily disassembled. The convenience of using optimum-sized modules has also been considered. Within this context, it should be mentioned that providing earthquake resistance to moment-resisting frames currently implies complicate beam-column connections with little disassemble potential.

In terms of sustainability, one of the tools that can be used to move away from heavy moment-resisting frames is the concept of damage-tolerant structures. Within this context, structural engineers can avoid complicate detailing of structural elements and connections, and come up with light and simple shop-made structural elements that can be easily assembled and disassembled in the field. In the case of structural steel, current state-of-the-practice can easily provide gravitational frames with high assembly/disassembly potential. In the case of reinforced concrete, the world-wide structural engineering community would have to start moving away from cast in-situ systems, and into precast ones.

5.1 Precast concrete

The use of precast concrete results in efficient construction processes that allow for the rapid construction of buildings. To fully understand the potential of precast concrete construction, it should be mentioned that precast concrete made possible in many ways the rapid re-construction of Europe after the Second World War, and has been extensively used by many European countries to accelerate their economical development after that war.

Compared to traditional cast in-situ systems, precast concrete does not only allow for rapid construction, but results in cleaner building sites, savings on formwork, better quality control, and the use of slimmer and more durable reinforced concrete structural elements. In terms of sustainability, this is reflected by lower direct costs and lower use of natural resources (in the short and long runs). Although this shows the potential contributions of precast concrete to sustainable development, for many years the design of precast structural systems has not been considered as an attractive structural alternative for earthquake-resistance.

In terms of the worries of researchers and practicing engineers, the detailing of the beam-column connections has received most of the attention. This has resulted in several proposals for complicate detailing of connections that have emphasized constructive and structural aspects. On one hand, experimental testing has consistently shown that well-detailed connections are capable of accommodating substantial lateral deformation (Rodriguez and Blandon 2001). Nevertheless and on the other hand, precast concrete frames lack an efficient and reliable mechanism to control the dynamic response of a building due to their pinched hysteretic behavior. In terms of sustainability, it is possible to complement all the advantages offered by a precast framed gravity system with those offered by the use of structural fuses. Within this context, structural engineers can move away from complicate cast in-situ beam-column connections, and promote the use of simpler connections with high disassembly potential.

5.2 Floor systems

In terms of economic and environmental savings, it is necessary to carefully consider the conception and design of the floor systems of a building. Although there are many available highly efficient floor systems, an interesting option in terms of sustainability is that formed by prefabricated gravitational pre-stressed beams and masonry units covered by a thin layer of reinforced concrete. This system has evolved into an attractive option for many housing units located in several Latin-American countries. Recently, the good capacity for temperature isolation of this system has given it commercial advantages with respect to traditional concrete slabs. This prefabricated floor system has also been used in larger structures, such as those that allocate commercial, business or industrial facilities; and it is expected to be more widely used in the next years due to the versatility and rapidity of its constructive process (Lopez *et al*. 2004). Modeling and design recommendations have been derived in Mexico from the analytic and experimental studies developed by the local community of structural engineering (Lopez *et al*. 2001, Rodriguez and Blandon 2003, Leon *et al*. 2008).

Although a prefabricated floor system allows important savings of material and a high efficiency during construction, it is important to consider during its design that it should behave as an in-plane rigid diaphragm. Within this context, the floor system should provide continuity to all elements that make up the prefabricated floor system, and exhibit sufficient in-plane stiffness and strength so that it can distribute the seismic forces among the different earthquake-resistant planes.

6. Sustainable earthquake-resistant design

Fig. 9 schematically illustrates a reinforced concrete building conceived and designed according to the vision developed in this paper. In summary, the main or gravitational system is made of precast frames made of standardized shop-manufactured structural elements fabricated with durable, high performance concrete or recycled materials. The floor system is made of prefabricated units topped with a reinforced concrete layer that plays the role of a structural diaphragm. Earthquake-resistance is provided by a system of structural fuses that is capable of adequately controlling the lateral response of the building. In terms of deconstruction and life cycle assessment, a standardized shop-manufactured building (including the gravitational and floor systems and the structural fuses) that can be practically assembled in situ can be disassembled for reuse, recycling or final disposal. Buildings such as that schematized in Fig. 9 constitute the basis over which the concept of sustainable earthquake-resistant design can be formulated. Note that similar concepts can be applied in the case of steel gravitational systems in terms of recycling and high disassembly potential. Curiously enough, a change of paradigm in earthquake-resistant design practices do not only result in important long term savings of non-renewable natural resources, but can result in green structural systems that have lower direct costs than traditional earthquake-resistant systems.

It is important to understand that the time horizon in which the vision developed in this paper can be applied to any country, including developing ones, is very short. First, the conceptual and theoretical use of structural fuses within the context of damage-tolerant structures is a well developed concept that can be immediately applied to the conception and design of buildings. Second, relatively simple concepts underlie the behavior and manufacturing of BR braces (several countries with different degree of development have carried successful studies on BR braces). Third, due to their extensive practical experience and the maturity of their current development, the communities of precast concrete and steel construction can contribute immediately to the concept of sustainable earthquake-resistant design and construction. Fourth, the studies developed in many

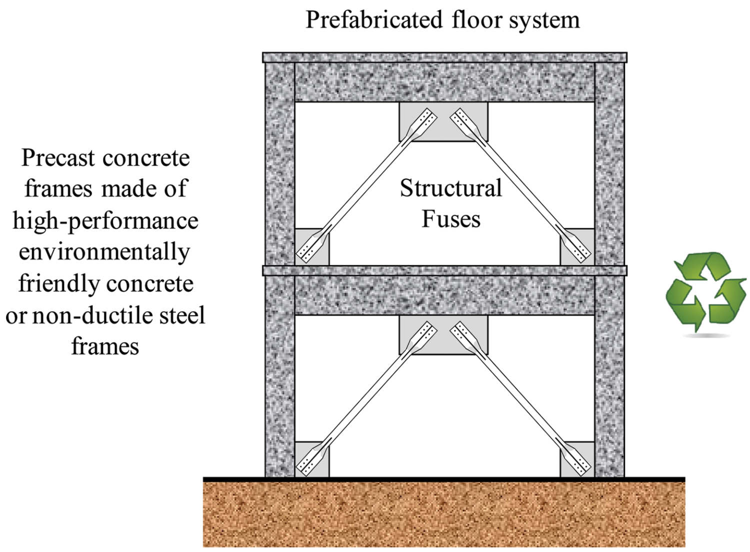

Fig. 9 Earthquake-resistant structural system for a green reinforced concrete building

countries on the use of innovative and recycled structural materials indicate the possibility of using them in the short run.

7. Conclusions

The presence of control devices in a building, such as the BR braces described herein, and the use of gravitational systems with high disassembly potential can represent a challenge from functional and aesthetical points of view. Under these circumstances, architectural and structural detailing may face difficulties, and discussions about the exact location of the control devices and the layout of the gravitational system require a close and respectful interaction between architects and structural engineers.

The role of the structural engineer is instrumental in making sustainable earthquake-resistant structural systems a reality at a large scale. Within this context, the international community of structural engineering should:

· *Change the earthquake-resistant design paradigm*. Earthquake-resistant design should give place to structural systems that are able to minimize in an optimal manner the economic and environmental cost of earthquakes, and not systems whose main goal is to achieve life safety or prevent collapse. This will only be possible if the international structural engineering community moves from current strength-based design of traditional systems to damage control-based design of highly efficient innovative structural systems.

· *Develop low-cost control devices.* The best option to achieve highly efficient earthquake-resistant structural systems is the conception of two independent and highly specialized structural sub-systems, one to carry the gravitational loads, and the other one to provide lateral vibration control. Within this context, each system can be conceived and designed to achieve its structural role with high efficiency in terms of structural materials. The use of this approach in developing nations at the massive scale implied by sustainability requires the local development of efficient, reliable and low-cost control devices. A good example of what can be achieved in this direction is the use of buckling-restrained braces.

· *Potentiate the concept of earthquake architecture*. No matter how much can be achieved in structural terms, the extensive use of sustainable earthquake-resistant structural systems will only be possible through a fruitful cooperation between structural engineers and architects. A concept that has the potential to catalyze a communication capable of promoting a deep and mutual understanding of the needs of both professions is that of earthquake architecture (Arnold 1996, Charleson and Taylor 2000, Charleson 2008). Earthquake architecture formulates the need to have an architectural expression that is particular to earthquake prone regions and, within this context, establishes the aesthetic possibilities that are offered by exposing the structural elements and technology that provide seismic resistance. Several authors have provided specific examples on how beauty and adequate seismic resistance can be achieved (Arnold 1996, Mezzi *et al*. 2004, Reitherman 2005, Charlesson 2008). Among other things that can be done, structural engineers may want to look into aesthetically enhancing, through the use of new materials, colors, textures and shapes, the basic geometry and appearance of the seismic control systems and their connections.

· *Improve methods for the assessment of the actual value of buildings.* The need and convenience of designing and constructing sustainable earthquake-resistant structural systems can only be understood through the correct assessment of the costs involved. In many senses, a rational decision from economic and sustainable points of view may not be taken because of limitations of current loss estimation procedures. Particularly, any loss estimation procedure that considers that a building has an initial cost that decreases its monetary value with time, ignores the undisputable fact that the environmental cost of that building, expressed in monetary terms or not, increases within that time horizon. Assessing the life cycle cost of a facility, including its replacement cost, may lead to design conclusions that are significantly different than those derived from current loss assessment methodologies (Arroyo *et al*. 2012).

Although there are many challenges for the implementation of safe sustainable earthquake-resistant structural systems, it can be said that the worldwide community of structural engineering can start contributing effectively and efficiently to the sustainable development of the world. In spite of this and with very few exceptions, earthquake prone countries are using traditional earthquake-resistant design methodologies and structural systems that at this point in the history of human development constitute an irrational waste of natural resources. In these terms, the largest obstacles that a structural engineer faces are not of technical nature, but are deeply rooted in his/her current perceptions on how buildings should survive earthquakes.

References

Alexander, M.G., Ballim, Y. and Stanish, K. (2008), "A framework for use of durability indexes in performancebased design and specifications for reinforced concrete structures", *Mater. Struct*., **41**(5), 921-936.

Arnold, C. and Riba, F. (1996), "Architectural aspects of seismic resistant design", *Proceedings of the 11th World Conference on Earthquake Engineering* (CD), 2003.

Arroyo, D., Ordaz, M. and Teran-Gilmore, A. (2012), "Seismic loss estimation including environmental losses", *Proceedings of the 14th World Conference on Earthquake Engineering* (CD), 2391.

Bertero, R. and Bertero, V.V. (1992), "Tall reinforced concrete buildings: conceptual earthquake-resistant design methodology", *Report No. UCB/EERC-92/16*, University of California at Berkeley.

Black, C., Makris, N. and Aiken, I. (2002), "Component testing, stability analysis and characterization of buckling-restrained unbounded braces", *Report PEER 2002/08*, University of California at Berkeley.

Charleson, A.W. and Taylor, M. (2000), "Towards an earthquake architecture", *Proceedings 12th World Conference on Earthquake Engineering* (CD), 0858.

Charleson, A. (2008), "Seismic design for architects, outwitting the quake", Elsevier Ltd., First Edition, ISBN: 978-0-7506-8550-4.

Chen, C.H., Hsiao, P.C., Lai, J.W., Lin, M.L., Weng, Y.T. and Tsai, K.C. (2004), "Pseudo-dynamic test of a fullscale CFT/BRB frame: Part 2 - Construction and testing", *Proceedings of the 13th World Conference on Earthquake Engineering* (CD), 2175.

Clark, P., Kasai, K., Aiken, I. and Kimura, I. (2000), "Evaluation of design methodologies for structures incorporating steel unbonded braces for energy dissipation", *Proceedings of the 12th World Conference on Earthquake Engineering* (CD), 2240.

Comerio, M.C. and Holmes, W.T. (2004), "Seismic risk reduction of laboratory contents", *Proceedings of the 13th World Conference on Earthquake Engineering* (CD), 3389.

Corinaldesi, V. and Moriconi, G. (2006), "Behavior of beam-column joints made of sustainable concrete under cyclic loading", *J. Mater. Civil Eng*., **18**(5), 650-658.

Di Prisco, M., Plizzari, G. and Vandewalle, L. (2009), "Fibre reinforced concrete: new design perspectives", *Mater. Struct*., **42**(9), 1261-1281.

Duxson, P., Provis, J.L., Lukey, G.C. and van Deventer, J.S.J. (2007a), "The role of inorganic polymer technology in the development of 'green concrete'", *Cement Concrete Res*., **37**(12), 1590-1597.

Duxson, P., Fernandez-Jimenez, A., Provis, J.L., Lukey, G.C., Palomo, A. and van Deventer, J.S.J. (2007b),

"Geopolymer technology: the current state of the art", *J. Mater. Sci*., **42**(9), 2917–2933.
Etxeberria, M., Mari, A.R. and Vazquez, E. (2007), "Recycled aggregate concrete as structural material", *Mater. Struct*., **40**(5), 529-541.
Federal Emergency Management Agency (2000), *Prestandard and commentary for the seismic rehabilitation of buildings*, *Report FEMA 356*, Washington, D.C.
Gao, W., Ariyama, T., Ojima, T. and Meier, A. (2001), "Energy impacts of recycling disassembly material in residential buildings", *Energ. Buildings*, **33**(6), 553-562.
Gartner, E. (2004), "Industrially interesting approaches to "low-CO2" cements", *Cement Concrete Res*., **34**, 1489-1498.
Gomes, M. and de Brito, J. (2009), "Structural concrete with incorporation of coarse recycled concrete and ceramic aggregates: durability performance", *Mater. Struct*., **42**(5), 663-675.
Johnson, E.A., Ramallo, J.C., Spencer, B.F. and Sain, M.K. (1998), "Intelligent base isolation systems", *Proceedings of the Second World Conference on Structural Control* (CD), 367-376.
Kaneko, M., Nakamura, Y., Kambara, H. and Tamura, K. (2008), "Seismic-safety evaluation method for building contents", *Proceedings of the 14th World Conference on Earthquake Engineering* (CD), S20-002.
Kelly, J.M. (1982), "The influence of base isolation on the seismic response of light secondary equipment", *Report No. UCB/EERC-81/17*, University of California at Berkeley.
Keoleian, G.A., Kendall, A., Dettling, J.E., Smith, V.M., Chandler, R.F., Lepech, M.D. and Li, V.C. (2005), "Life cycle modeling of concrete bridge design: comparison of engineered cementitious composite link slabs and conventional steel expansion joints", *J. Infrastruct. Syst*., **11**(1), 51-60.
Kiggins, S. and Uang, C.M. (2006), "Reducing residual drift of buckling-restrained braced frames as a dual system", *Eng. Struct*., **28**(11), 1525-1532.
Kneer, E. and Maclise, L. (2008), "Consideration of building performance in sustainable design: a structural engineer's role", *Proceedings SEAOC 2008 Convention*.
Ko, E., Mole, A., Aiken, I., Tajirian, F., Rubel, Z. and Kimura, I. (2002), "Application of the unbonded brace in medical facilities", *Proceedings of the 7th National Conference on Earthquake Engineering* (CD), 514.
Konstantinidis, D. and Makris, N. (2006), "Experimental and analytical studies on the seismic response of freestanding and restrained laboratory equipment", *Proceedings of the 8th U.S. National Conference on Earthquake Engineering* (CD), 1619.
Levy, S.M. and Helene, P. (2004), "Durability of recycled aggregates concrete: a safe way to sustainable development", *Cement Concrete Res*., **34**(11), 1975-1980.
Leon Flores, G.A., Lopez Batiz, O. and Padilla Romero, D.A. (2008), "Estudios experimentales del comportamiento sísmico de losas prefabricadas", *Proceedings of the 16th Mexican Conference on Structural Engineering* (In Spanish), CD.
Li, V.C. (2007), "Integrated structures and materials design", *Mater. Struct*., **40**(4), 387-396.
Lopez Batiz, O., Cazamayor Cazares, A.H., Ortiz Vazquez, E. and Silva Olivera, H. (2001), "Estudio experimental sobre el comportamiento de estructuras con sistema de piso de vigueta y bovedilla sujetas a cargas laterales", *Proceedings of the 13th Mexican Conference on Seismic Engineering* (In Spanish), CD.
Lopez, W., Gwie, D., Saunders, M. and Lauck, T. (2002), "Lessons learned from large-scale tests of unbonded braced frame subassemblage", *Proceedings of the SEAOC 71st Annual Convention* (CD).
Lopez Batiz, O., Hernandez Diaz, J.L. and Peña Pedroza, J.I. (2004), "Desempeño de estructuras de concreto reforzado precoladas y presforzadas ante cargas laterales", *Proceedings of the 14th Mexican Conference on Structural Engineering* (In Spanish), CD.
Mahin, S., Uriz, P., Aiken, I., Field, C. and Ko, E. (2004), "Seismic performance of buckling restrained braced frame systems", *Proceedings of the 13th World Conference on Earthquake Engineering* (CD), 1681.
Marsantyo, R., Shimazu, T. and Araki, H. (2000), "Dynamic response of nonstructural systems mounted on floors of buildings", *Proceedings of the 12th World Conference on Earthquake Engineering* (CD), 1872.
Martinez-Soto, I.E. and Mendoza-Escobedo, C.J. (2006), "Comportamiento mecánico de concreto fabricado con agregados reciclados", *Invest. Tecnol*., **7**(3), 151-164.
Mezzi, M., Verducci, P. and Liu, J.J. (2004), "Innovative systems for a sustainable architecture and engineering", *Proceedings of the IABSE Symposium "Metropolitan Habitats and Infrastructure"*.
Moehle, J.P. (1992), "Displacement-based design of RC structures subjected to earthquakes", *Earthq. Spectra*,

8(3), 403-428.
Montiel Ortega, M.A. and Teran-Gilmore, A. (2011), "Comparative reliability of two twenty-four story braced buildings: traditional versus innovative", *Struct. Des. Tall Spec.*, DOI: 10.1002/tal.716.
Moon, K.S., Connor, J.J. and Fernandez, J.E. (2007), "Diagrid structural systems for tall buildings: characteristics and methodology for preliminary design", *Struct. Des. Tall Spec.*, **16**(2), 205-230.
Oikonomou, N.D. (2005), "Recycled concrete aggregates", *Cement Concrete Comp.*, **27**(2), 315-318.
Priestley, M., Calvi, G.M. and Kowalsky, M.J. (2007), "Displacement-based seismic design of structures", IUSS PRESS, Pavia, ITALY.
Reitherman, R. (2005), "Lateral thinking, both ways, for both objectives", Pamphlet Architecture Entry.
Rodríguez, M. and Blandón, J.J. (2001), "Diseño y comportamiento sísmico de edificios a base de muro-marco de concreto reforzado. Aplicación a la prefabricación", *Proceedings of the 13th Mexican Conference on Seismic Engineering* (In Spanish), CD.
Rodriguez, M. and Blandon, J. (2003), "Sistemas de piso en edificaciones para resistir fuerzas sísmicas en su plano", *Proceedings of the 14th Mexican Conference on Seismic Engineering* (In Spanish), CD.
Santa-Ana, P.R. and Miranda, E. (2000), "Strength-reduction factors for multi-degree-of-freedom systems", *Proceedings of the 12th World Conference on Earthquake Engineering* (CD), 1446.
Siddique, R. and Naik, T.R. (2004), "Properties of concrete containing scrap-tire rubber - an overview", *Waste Manage.*, **24**(6), 563-569.
Somerville, P.G., Smith, N., Punyamurthula, S. and Sun, J. (1997), "Development of ground motion time histories for phase 2 of the FEMA/SAC Steel Project", *Report SAC/BD-97/04*, SAC Joint Venture.
Soong, T.T. and Spencer, B.F. (2002), "Suplemental energy dissipation: state-of-the-art and state-of-the practice", *Eng. Struct.*, **24**(3), 243-259.
Takahashi, N. and Shiohara, H. (2004), "Life cycle economic loss due to seismic damage of nonstructural elements", *Proceedings of the 13th World Conference on Earthquake Engineering* (CD), 203.
Teran-Gilmore, A. and Virto Cambray, N. (2009), "Preliminary design of low-rise buildings stiffened with buckling restrained braces by a displacement-based approach", *Earthq. Spectra*, **25**(1), 185–211.
Teran-Gilmore, A. and Coeto, G. (2011), "Displacement-based preliminary design of tall buildings stiffened with a system of buckling-restrained braces", *Earthq. Spectra*, **27**(1), 153-182.
Teran-Gilmore, A. and Ruiz-Garcia, J. (2010), "Comparative seismic performance of steel frames retrofitted with buckling-restrained braces through the application of force-based and displacement-based approaches", *Soil Dyn. Earthq. Eng.*, **31**(3), 478-490.
Thormark, C. (2001), "Conservation of energy and natural resources by recycling building waste", *Resour. Conserv. Recy.*, **33**(2), 113-130.
Thormark, C. (2002), "A low energy building in a life cycle - its embodied energy, energy need for operation and recycling potential", *Build. Environ.*, **37**(4), 429-435.
Thormark, C. (2006), "The effect of material choice on the total energy need and recycling potential of a building", *Build. Environ.*, **41**(8), 1019-1026.
Tremblay, R., Degrange, G. and Blouin, J. (1999), "Seismic rehabilitation of a four-story building with a stiffened bracing system", *Proceedings of the 8th Canadian Conference on Earthquake Engineering* (CD).
Tremblay, R., Bolduc, P., Neville, R. and DeVall, R. (2006), "Seismic testing and performance of buckling restrained bracing systems", *Can. J. Civil Eng.*, **33**(2), 183-198.
Turki, M., Naceur, I.B., Makni, M., Rouis, J. and Saï, K. (2009), "Mechanical and damage behavior of mortarrubber aggregates mixtures: experiments and simulations", *Mater. Struct.*, **42**(10), 1313-1324.
Uang, C.M. and Nakashima, M. (2003), "Steel buckling-restrained braced frames", Earthquake Engineering: Recent Advances and Applications, Chapter 16, CRC Press.
United Nations (1987), "Report of the world comission on environment and development", General Assembly Resolution, 96th Plenary Meeting.
Ventura, C.E., Liam-Finn, W.D., Lord, J.F. and Fujita, N. (2003), "Dynamic characteristics of a base isolated building from ambient vibration measurements and low level earthquake shaking", *Soil Dyn. Earthq. Eng.*, **23**(4), 313-322.
Villaverde, R. (1997), "Seismic design of secondary structures: state of the art", *J. Struct. Eng.-ASCE*, **123**(8), 1011-1019.

Wada, A., Huang, Y. and Bertero, V.V. (2003), "Innovative strategies in earthquake engineering", Earthquake Engineering: Recent Advances and Applications, Chapter 10, CRC Press.
Walraven, J.C. (2009), "High performance fiber reinforced concrete: progress in knowledge and design codes", *Mater. Struct*., **42**(9), 1247-1260.
Watanabe, A., Hitomi, Y., Saeki, E., Wada, A. and Fujimoto, M. (1988), "Properties of brace encased in buckling-restraining concrete and steel tube", *Proceedings of the 9th World Conference on Earthquake Engineering*, 719-724.
Wikipedia (2011), "Hearst tower (New York City)" http://en.wikipedia.org/wiki/Hearst_Tower_(New_York_City)
World Steel Association (2007), "A global sector approach to CO_2 emissions reduction for the steel industry", http://www.worldsteel.org/?action=storypages&id=226.

CC